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(54) Method of Tracking Dynamic Communication Parameters during a Link Interruption

(57) In a mobile communication system (90) wherein communication parameters vary appreciably between transmissions, subscriber units (200) are susceptible to link blockages resulting in a loss of successive feedback instructing subscriber units (200) of adjustments to communication parameters to be employed in a subsequent transmission on a communication link (105). When a mobile subscriber unit (200) is airborne, an outage may occur from a control surface blockage during maneuvering. Aircraft avionics (290) supplies acceleration data representing aircraft movement for use in predicting subsequent communication parameters. These predicted parameters are employed in re-establishing communications upon the removal of such a link blockage.

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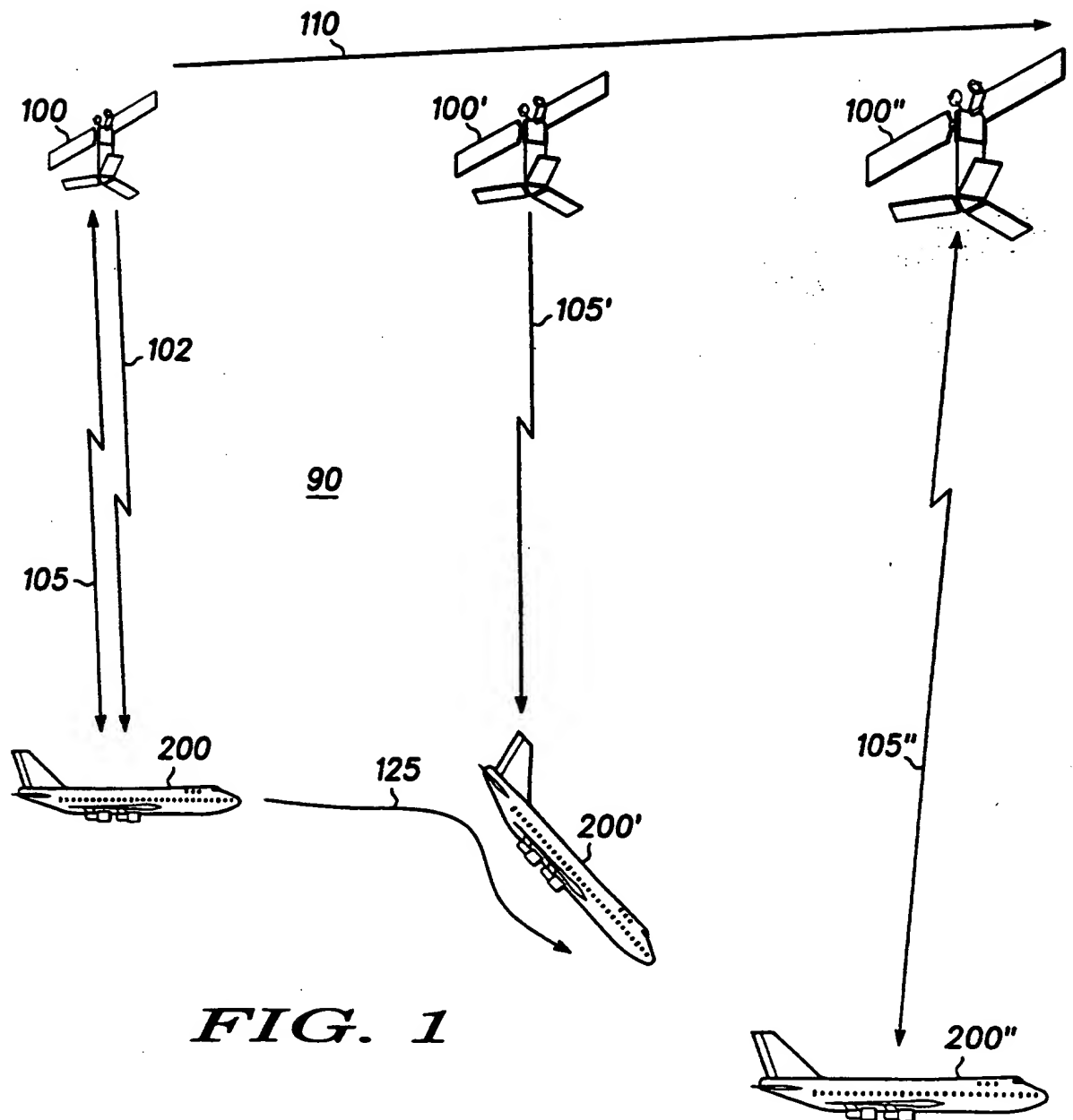


FIG. 1

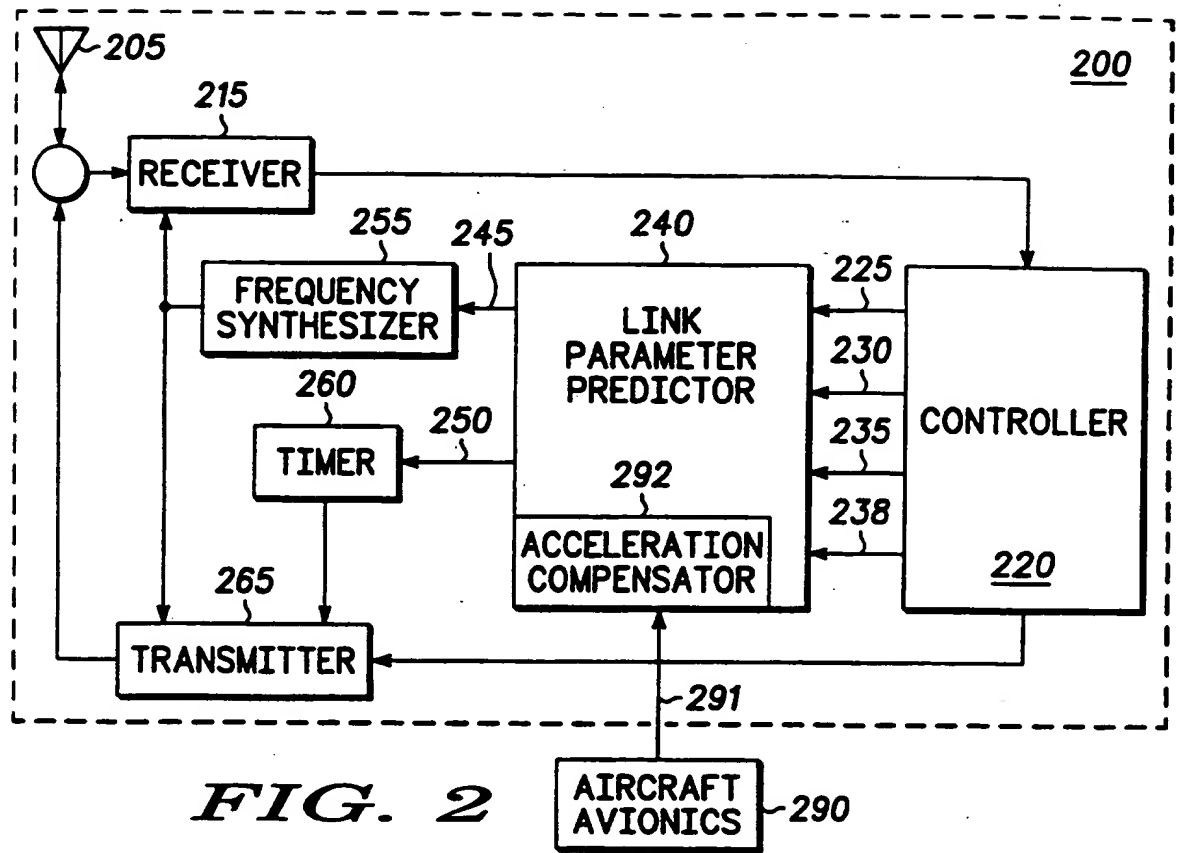


FIG. 2

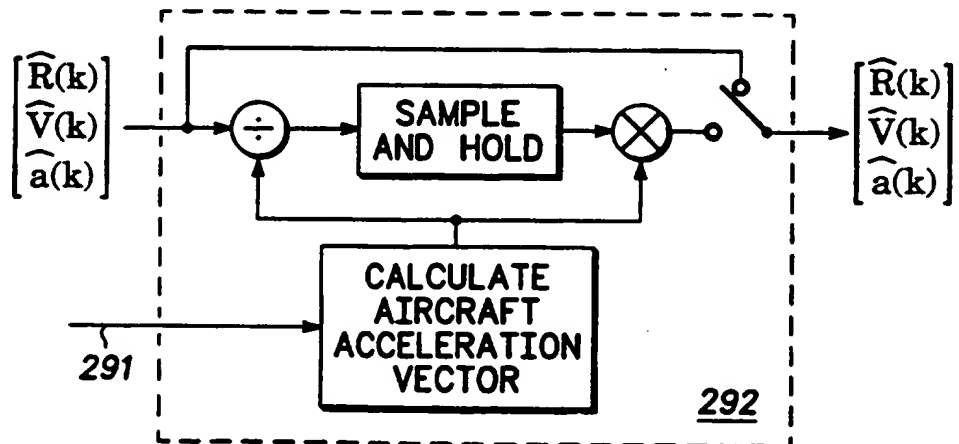


FIG. 5

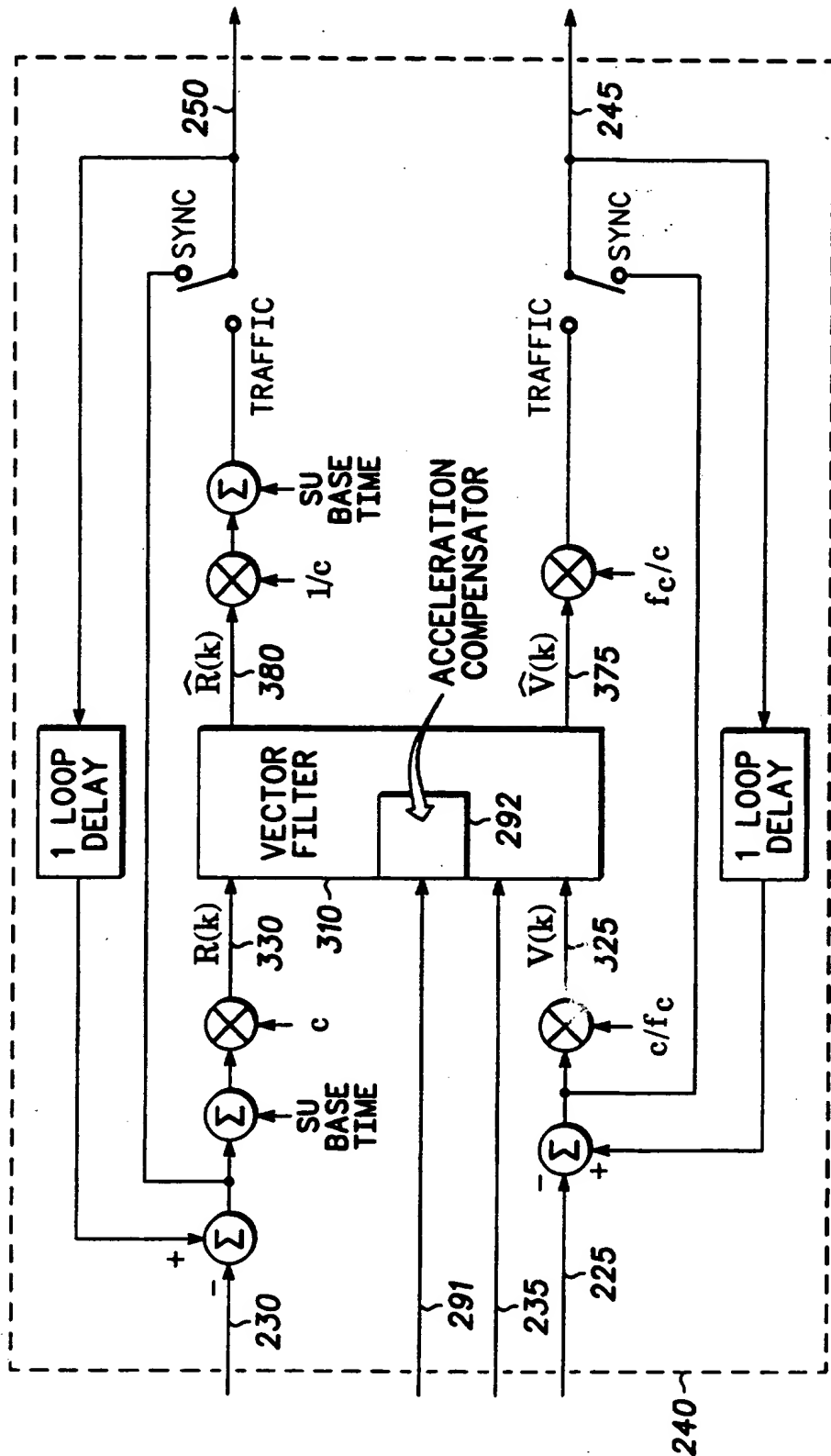


FIG. 3

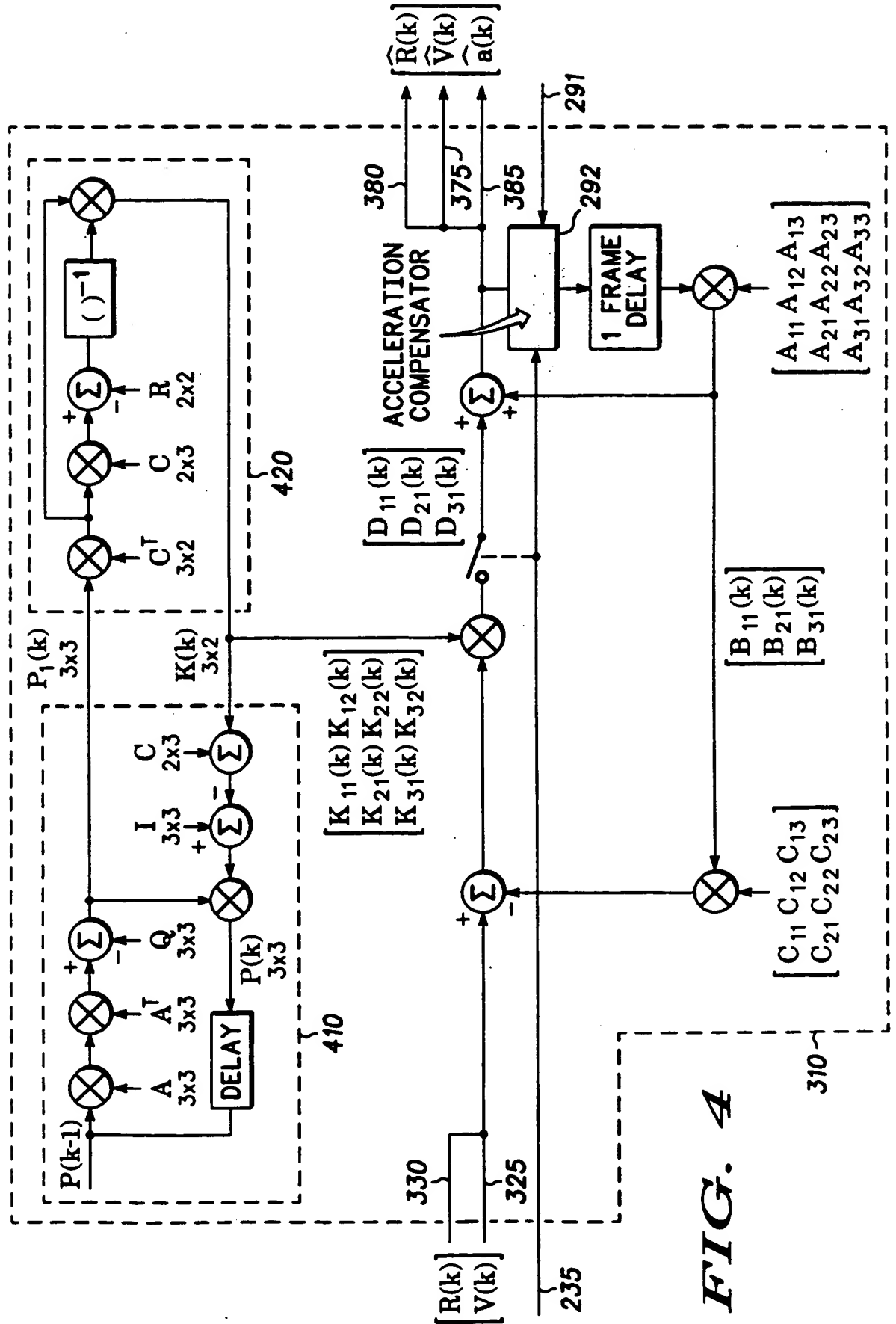
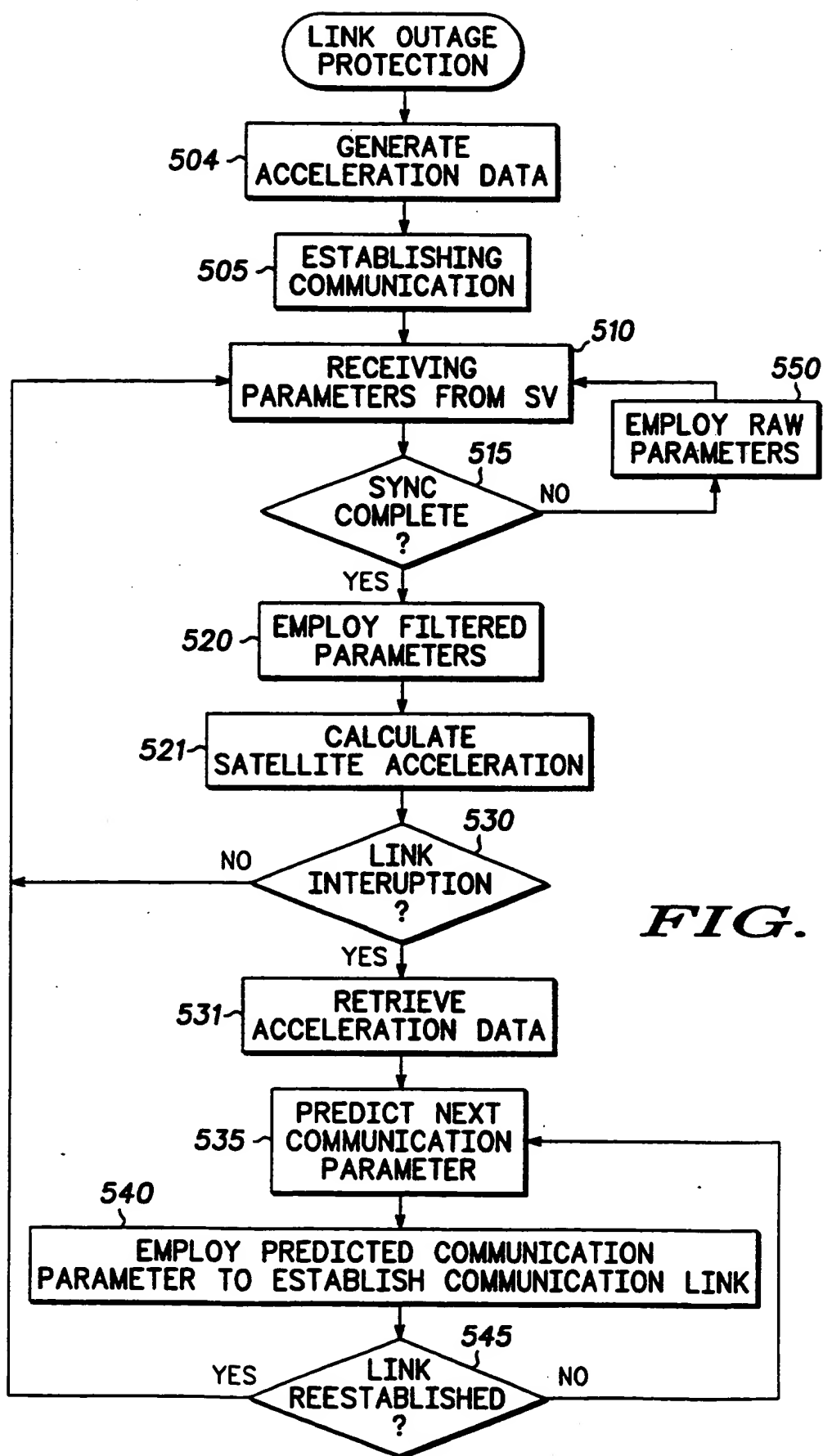


FIG. 4

**FIG. 6**

METHOD AND SYSTEM OF TRACKING DYNAMIC COMMUNICATION
PARAMETERS DURING A LINK INTERRUPTION

5 RELATED INVENTIONS

The present invention is related to the following invention which is assigned to the same assignee as the present invention:

- 10 (1) Method and Parameter Prediction System for Reestablishing a Temporarily Interrupted Dynamic Communication Link, U.K. 9613529.8.

15 FIELD OF THE INVENTION

This invention relates generally to telecommunications, and in particular, to established temporarily-interrupted communication links in an
20 dynamic telecommunication system where communication parameters such as Doppler frequency offset and propagation delay are time-variant.

25 BACKGROUND OF THE INVENTION

In telecommunication systems, links are established between nodes of a system for conveying information. Efficient use of these links requires enforcement of
30 communication parameters defining when nodes at each end of a link anticipate information from the other unit. These parameters, in efficient bandwidth systems, comply with extremely tight tolerances to maximize information exchange. These parameters may include propagation
35 delay between nodes of a network and transmit frequencies combined with any path introduced frequency error such as Doppler frequency shifts. As the

communication parameters of the interfacing nodes become more predictable and precise, guardbands on communication channels such as frequency and timeslots can be reduced to accommodate exchange of additional
5 information.

In conventional static or lightly dynamic telecommunication networks, these communication parameters may be refined upon the establishment of a communication link and relied upon throughout a
10 communication session. However, in a dynamic communication system where these communication parameters are rapidly changing, communicating nodes such as subscriber units must continually refine and update these communication parameters in order to
15 maintain the prescribed tolerances of the system.

Many systems evaluate each transmission employing dynamic communication parameters to determine the precision of the employed parameters. When the parameters exceed a threshold value as defined by system
20 specifications such as channelized communication frequencies or timeslots, the receiving system informs the transmitting node of correction values necessary to bring the communication parameters into compliance with the system requirements.

This approach is suitable when established communication links are not susceptible to transient effects such as temporary outages due to obstructions or fleeting interference. However, in dynamic
communication systems where communication parameters are short-lived, even brief outages of communication links
30 cause communication parameters to become stale and ineffective when utilized following communication link outages. A node such as a subscriber unit that employs out-dated communication parameters will not be
35 recognized by a receiving system due to the precise tolerances of channelized communication systems. When a subscriber unit is not recognized, the communication

link will be terminated. Reestablishing a communication link is both inefficient and annoying for communication link users.

Furthermore, systems that attempt to predict
5 communication parameters based on historical values, may be ineffective when a communication link is interrupted and one of the communication nodes such as a subscriber unit unpredictably alters its direction of travel causing an introduction of unanticipated Doppler
10 frequency and timing variations. The prediction of communication parameters then becomes ineffective when the link obstruction ceases.

Accordingly, there is a significant need for a method and apparatus for predicting dynamic
15 communication parameters continuously throughout a brief outage such that when the outage is terminated, a subscriber unit will have revised its dynamic communication parameters to comply with the current system dynamics. The subscriber unit may then
20 immediately employ these revised dynamic communication parameters in subsequent transmissions to a receiving unit. The receiving unit will recognize and process the received communications since the revised communication parameters are in compliance with system parameters,
25 thus foregoing the need to establish a subsequent communication link.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 depicts a highly simplified diagram of a
5 dynamic communication system of which the present
invention may form a portion thereof;

FIG. 2 depicts a block diagram of mobile subscriber
unit in a dynamic communication system of which the
present invention may form a portion thereof;

10 FIG. 3 depicts a block diagram of a communication
parameter predictor for a subscriber unit of which the
present invention may form a portion thereof;

FIG. 4 depicts a block diagram of a vector filter
for a communication parameter predictor of which the
15 present invention may form a portion thereof;

FIG. 5 depicts a block diagram of an acceleration
compensator in accordance with a preferred embodiment of
the present invention; and

FIG. 6 is a flowchart for predicting dynamic
20 communication parameters in a dynamic communication
system, in accordance with a preferred embodiment of the
present invention.

25 DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention has utility in immediately
resuming communication services upon interruption of a
communication link between a mobile base station and a
30 mobile subscriber unit in a communication system wherein
the mobile base station and the mobile subscriber unit
are dynamically oriented. In a satellite communication
system, the dynamic orientation would be due to the
orbiting nature of the satellite in relationship to the
35 Earth-bound or near Earth-bound subscriber unit. In the
preferred embodiment, the mobile subscriber unit is

highly mobile such as is characteristic of a subscriber unit located within an aircraft.

FIG. 1 depicts a highly simplified diagram of a dynamic communication system of which the present invention may form a portion thereof. A dynamic communication system 90 has components or nodes that are dynamically oriented such that distances and velocities are changing between the nodes. In FIG. 1, dynamic communication system 90 is shown as an orbiting satellite-based system where satellites 100 represent one of the communication nodes or mobile base stations and in the preferred embodiment are space-born. It is also practical that dynamic communication system 90 could have air-born nodes or even that nodes could be Earth-bound but still in motion in relationship to other nodes. Mobile subscriber unit 200 forms the other end of communication link 105 in dynamic communication system 90.

The motion or dynamics between nodes creates the dynamic communication parameters necessary for effective and efficient communication in an efficient system. Satellite 100 orbits the Earth in satellite orbit 110. The term "satellite" is intended to include orbiting satellites such as low-Earth orbiting (LEO) satellites, medium-Earth orbiting (MEO) satellites, or highly-inclined orbit (HIO) satellites.

Satellite 100 in satellite orbit 110 orbits the Earth at an altitude of around 780 km in a LEO system. This low-Earth orbit translates into a velocity with respect to the Earth of around 25,000 km/hr. Such a velocity allows satellite 100 to be in view of a terrestrial node such as mobile subscriber unit 200 for a duration of only around nine minutes. This velocity creates very dynamic communication parameters such as Doppler frequency shift and propagation delay or timing. With such a variation on communication parameters, mobile subscriber unit 200 must frequently revise its

communication parameters to comply with the system timing as expected by satellite 100.

In order to establish communication link 105, mobile subscriber unit 200 uses default or initial communication parameters. These parameters may be either derived from observations of the broadcast channel, pre-programmed into mobile subscriber unit 200 or may be received by mobile subscriber unit 200 on an independent broadcast channel 102. Such a channel is a broadband channel that is uni-directional from satellite 100. Broadcast channels may carry other system managing information broadcast to all mobile subscriber units within view of satellite 100.

Mobile subscriber unit 200 uses default communication parameters as an approximation to actual communication parameters. This transmission to satellite 100 occurs generally on a secondary or acquisition channel having a much lower bandwidth and broader tolerances for both frequency and time variations. Satellite 100 evaluates the transmission by mobile subscriber unit 200 which employed default communication parameters. Satellite 100, in a subsequent transmission to mobile subscriber unit 200, returns the result of this evaluation to mobile subscriber unit 200 in the form of feedback communication parameters denoting necessary adjustments to the default communication parameters. In the preferred embodiment, these feedback communication parameters are frequency-of-arrival (FOA) raw parameter 225 (FIG. 2) and time-of-arrival (TOA) raw parameter 230 (FIG. 2). These parameters denote a differential value of the expected frequency and timing received at satellite 100 and the actual measured values at satellite 100. Mobile subscriber unit 200 revises the default communication parameters according to the feedback information. Mobile subscriber unit 200 in subsequent transmissions to satellite 100 employs the

revised communication parameters. This refining process repeats until dynamic communication parameters have been sufficiently refined to enable non-interfering transmission on a narrow-band channel. Satellite 100 then directs mobile subscriber unit 200 to a traffic channel and establishment of communication link 105 is complete. This process continues to be iteratively performed as necessary to maintain the communication link parameters on the narrow band traffic channel.

FIG. 1 also depicts satellite 100 in motion with respect to mobile subscriber unit 200 and the potential for an outage of communication link 105. At a first point in time, satellite 100 and mobile subscriber unit 200 are shown to have an active established communication link 105.

As mobile subscriber unit 200, traveling in mobile subscriber unit direction of travel 125, obstructs communication link 105' either by banking thus causing a aircraft wing obstruction as in the case of an agile aircraft or passes by an obstruction such as a mountain, communication link 105' experiences an outage with mobile subscriber unit 200'. For example, in airborne applications, a link outage may occur due to control surface blockage of the link while the aircraft performs a maneuver. After the aircraft completes the maneuver, the line of sight to the link is reestablished. Unlike the ground mobile subscriber cases, the aircraft dynamics are not necessarily negligible compared to the satellite dynamics.

Also, the aircraft dynamics are time varying during the outage time and simple constant parameters are not accurate enough for link prediction. For example, as an aircraft executes a turn, the aircraft first rolls and then the turn gradually ensues. Early in the roll, the link may become blocked by a control surface, i.e. by the wing. If the filter locked-in estimates of the dynamics at this point, it would under estimate the

dynamics of the actual turn and not correctly predict the link parameters. In order to correctly predict the link parameters, the loop tracking filter must account for the radial acceleration of the link which comprises the satellite and the aircraft accelerations.

When mobile subscriber unit 200'' emerges from or ceases to create an obstruction, both satellite 100'', in satellite orbit 110, and mobile subscriber unit 200'', in direction of travel 125 have substantially changed their orientations with respect to each other. If an obstruction obscures communication link 105 for even a second in a narrow-band LEO satellite communication system, employment by mobile subscriber unit 200'' of the dynamic communication parameters utilized at the locations of satellite 100 and mobile subscriber unit 200, would be out of the tolerances required by communication link 105''. The need for revising and predicting dynamic communication parameters becomes apparent as mobile subscriber unit 200 operates in a dynamic environment such as onboard aircraft.

FIG. 2 depicts a block diagram of mobile subscriber unit 200 in a dynamic communication system 90 (FIG. 1) of which the present invention may form a portion thereof. A receiver 215 receives, through antenna 205, broadcast channel 102 (FIG. 1) which may explicitly contain default communication parameters or be used to derive communication parameters. Receiver 215 buffers all received transmissions from satellite 100, such as broadcast channel information, acquisition channel information, and information on communication link 105.

A controller 220 receives the buffered information from receiver 215. Controller 220 parses this information to extract default or feedback communication parameters from the received signal. In a preferred embodiment, dynamic communication parameters are comprised of frequency and timing or propagation parameters. Controller 220 sends FOA raw parameter 225

and TOA raw parameter 230 to a communication parameter predictor 240. Controller 220 also evaluates the status of communication link 105 (FIG. 1) and generates a link detect status 235 denoting whether an outage is
5 underway.

In the preferred embodiment where mobile subscriber unit 200 is located on an aircraft, aircraft avionics 290 generates acceleration data 291 for use by acceleration compensator 292 during a link outage. Link
10 detect status 235 also enables acceleration data 291 to be processed in the vector filter for generation of predicted communication parameters during a link outage.

During the tracking process for maintaining a communication link, raw feedback communication
15 parameters are employed in transmissions to "pull" timing and frequency of mobile subscriber unit transmissions into compliance with tight tolerances of the traffic channels of communication link 105. The use of raw feedback parameters allows subscriber unit 200 to
20 quickly adjust communication parameters in gross steps as compared with finer predicted incremental values capable from the vector filter of the present invention.

Communication parameter predictor 240 receives the parameter and status signals and processes them to
25 generate predicted frequency parameter 245 and predicted timing parameter 250. These signals inform frequency synthesizer 255 and timer 260 of the requisite transmission characteristics required to have information transmitted by transmitter 265 of subscriber
30 unit 200 on communication link 105 received at satellite 100 during the proper channel (i.e., frequency and timeslot in a channelized system).

FIG. 3 depicts a block diagram of a communication parameter predictor for a mobile subscriber unit of
35 which the present invention may form a portion thereof. Communication parameter predictor 240 improves the performance of mobile subscriber unit 200 by providing a

smoothing and predicting vector filter 310. Vector filter 310 acts upon range measurements ($R(k)$) 330 and velocity measurements ($V(k)$) 325 and produces smoothed estimates of the range and velocity of satellite 100 relative to subscriber unit 200.

Frequency-of-arrival raw parameter 225 and time-of-arrival raw parameter 230 are converted to range and velocity measurements in communication parameter predictor 240 for use by vector filter 310. The speed of light, c , and a subscriber unit base time defining a reference from which subscriber unit transmission and reception timing are based, are used in converting time-of-arrival parameters to and from range parameters. Smoothed and predicted range estimate 380 and predicted velocity estimate 375 are converted back to predicted frequency parameter 245 and predicted timing parameter 250 for use by frequency synthesizer 255 (FIG. 2) and timer 260 (FIG. 2).

FIG. 3 also shows the bypass switching of vector filter 310 as controlled by synchronization complete status 238 during the synchronization "pull-in" phase, as described above in FIG. 2, for establishing communication link 105 (FIG. 1). During synchronization, communication parameter predictor 240 operates with vector filter 310 out of the loop. At this point in the operation, the use of a smoothing filter is pointless. After "pull-in" is achieved and the mode is switched from sync to traffic, vector filter 310 is switched on provided sufficient raw measurements have been made to initialize the state vector of the vector filter. Initialization of vector filter 310 is discussed in FIG. 4. The structure of communication parameter predictor 240 converts TOA raw parameter 230 (FIG. 3) and FOA raw parameter 225 (FIG. 3) into a raw range parameter 330 and a raw velocity parameter 325 and both are input to vector filter 310 as a 2×1 matrix.

FIG. 4 depicts a block diagram of a vector filter for a communication parameter predictor 240 of which the present invention may form a portion thereof. A preferred embodiment of vector filter 310 is shown as a three-state filter. Other numbers of states may be implemented for increased accuracy. In vector filter 310, acceleration is the third state and the dynamically random process is now the rate of change of acceleration. Other filters that could be considered to further improve performance would be four or more states or an extended Kalman filter.

The design of a filter requires both a model for the physical process and a model for the observation process. The physical process model is selected to incorporate as much information as possible about the relationships between range, range-rate, range-rate-rate, etc. The more sophisticated the model, the more complex the filter and the better the tracking results. The observation model is based upon the measurements available to the system and the noise process that is corrupting these measurements.

For a vector filter, the process model expressed as a first order vector dynamic equation is:

$$x(k+1) = A x(k) + w(k)$$

where $w(k)$ is the physical model noise process. Its covariance matrix is defined by:

$$Q(k) = E\{w(k) w^T(k)\}$$

The observation model is given by:

$$y(k) = C x(k) + z(k),$$

where $z(k)$ is the measurement noise process. The measurement noise covariance matrix is defined by:

$$R(k) = E\{z(k) z^T(k)\}$$

The Kalman filter estimator of $x(k)$ given its previous value, $x(k-1)$, is given by:

$$x(k) = A x(k-1) + K(k)[y(k) - C A x(k-1)]$$

where the gain matrix is:

$$K(k) = P_1(k) C^T [C P_1(k) C^T + R(k)]^{-1}$$

where,

$$P_1(k) = A P(k-1) A^T + Q(k-1)$$

$$P(k) = P_1(k) - K(k) C(k) P_1(k)$$

5 The discrete time difference equation for acceleration is found by expressing the acceleration at time $(k+1)T$ as the acceleration at time kT plus T times the acceleration rate of change. Mathematically the radial acceleration, $a(k)$ is:

10 $a(k+1) = a(k) + T a'(k)$

where,

$a'(k)$ is the rate of change of radial acceleration at time kT .

Integrating acceleration to find velocity, $v(k)$:

15 $v(k+1) = v(k) + T a(k) + \frac{T^2}{2} a'(k)$

Integrating again to find slant range, $r(k)$:

$$r(k+1) = r(k) + T v(k) + \frac{T^2}{2} a(k) + \frac{T^3}{6} a'(k)$$

$a'(k)$

Defining,

20 $x(k) = \begin{bmatrix} r(k) \\ v(k) \\ a(k) \end{bmatrix} = \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix}$

$$x_1(k+1) = x_1(k) + T x_2(k) + \frac{T^2}{2} x_3(k) + \frac{T^3}{6} a'(k)$$

$a'(k)$

$$x_2(k+1) = x_2(k) + T x_3(k) + \frac{T^2}{2} a'(k)$$

$$x_3(k+1) = x_3(k) + T a'(k)$$

25 Expressed in matrix notation:

$$x(k+1) = \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} x(k) + \begin{bmatrix} \frac{T^3}{6} \\ \frac{T^2}{2} \\ T \end{bmatrix} a'(k)$$

which is the first order vector equation. Hence,

$$A = \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \quad ; \text{ and } \quad w(k) = \begin{bmatrix} \frac{T^3}{6} \\ \frac{T^2}{2} \\ T \end{bmatrix} \quad a'(k)$$

Since independent observations of range and velocity are made via the time and frequency tracking loops, respectively, the observation equation is:

$$5 \quad y(k) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} x(k) + z(k)$$

which defines the 2x3 C-matrix for this implementation,

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

10 As mentioned above, the structure of communication parameter predictor 240 converts TOA raw parameter 230 (FIG. 3) and FOA raw parameter 225 (FIG. 3) into a raw range parameter 330 and a raw velocity parameter 325 and are input to vector filter 310 as a 2x1 matrix. A
15 feedback path is added to the input and multiplied by the 3x2 gain matrix K. The result is a 3x1 matrix denoted by D. The 3x1 matrix B is added to D to yield the output 3x1 matrix which is the smoothed estimate of range, velocity and acceleration. The B and D matrices
20 are storage medium and do not appear directly in the vector filter equations.

Communication parameter predictor 240 and its inclusive vector filter 310 must operate through periods of time when no data is available for input but an
25 updated estimate is still needed for the tracking loop. This occurs routinely when coasting in-between maintenance bursts containing feedback communication parameters or sporadically when communication link 105 blockages occur. The availability of a measurement can
30 be determined by link detect status 235. When available, vector filter 310 operates closed loop and all covariance matrices are updated. When no data is available, the feedback tap from the loop gain matrix is

opened, the gain matrix and covariance matrices are not updated, and the estimate is formed from the geometric matrix A, the previous state estimate matrix, and acceleration compensation data from aircraft avionics such as an aircraft inertial navigation system.

Since the state variables are updated at the frame rate and the gain and covariance matrices are updated at the maintenance schedule rate which is every fourth frame in the preferred embodiment, two A matrices must be maintained. The matrix for the state variable calculations is designated as A1 and is given by:

$$A1 = \begin{bmatrix} 1 & T_1 & T_1^2/2 \\ 0 & 1 & T_1 \\ 0 & 0 & 1 \end{bmatrix}$$

The matrix for the gain and covariance matrix calculations is computed for a four frame interval. It is designated as matrix A4 and is given by:

$$A4 = \begin{bmatrix} 1 & T_4 & T_4^2/2 \\ 0 & 1 & T_4 \\ 0 & 0 & 1 \end{bmatrix}$$

Gain Matrix and Error Covariance Matrix Computation

The procedure for computing the error covariance matrices, P and P1, of an error covariance matrix computation block 410 is discussed below. The first time the loop is executed, an initial value for the P matrix, P(0), must be available. The initialization values used are discussed in a later section. From this, P1(1) is computed. The gain matrix, K(1), of a gain matrix computation block 420 is then computed and used in the filter loop of vector filter 310 to update the state variable estimates. The gain matrix is also used to update the P matrix, P(1), which is stored until the next time the loop is executed.

Upon subsequent executions of the loop, the previous value of the P(k) is used in the P1(k) and K(k) computation rather than the initial value matrix.

However, if it is determined by subscriber unit 200 that a link outage has occurred then the P matrix will be set back to P(0). This allows reinitialization of the error variances back to their initial values and increases the loop gain to facilitate rapid reacquisition of the uplink from subscriber unit 200 to satellite 100.

Mobile subscriber unit 200 should also reset the state vector to initial values after a link outage. Initial values are determined by feedback communication parameters after communication link 105 is re-established.

A simplification of the P matrix computation is shown implemented in error covariance matrix computation block 410 and is defined by substituting the values for the C matrix and factoring P₁ from the equation:

$$\begin{aligned} P(k) &= P_1(k) - K(k) C(k) P_1(k) \\ &= [I - K(k) C(k)] P_1(k) \\ &= \begin{bmatrix} 1-K_{11}(k) & K_{12}(k) & 0 \\ K_{21}(k) & 1-K_{22}(k) & 0 \\ K_{31}(k) & K_{32}(k) & 1 \end{bmatrix} P_1(k) \end{aligned}$$

As the P matrix is iterated over and over again, its entries will stabilize to their steady state values. The entries in the P matrix change from their initial error variances of the estimates to their final values.

A gain matrix computation block 420 is shown in FIG. 4. The K matrix is computed from the P₁ matrix and the other constants C and R. The dimensionality of each matrix used in the computation is also shown. Note that even though a 3-state filter is implemented in the preferred embodiment, the inverse function acts on only a 2x2 matrix. As vector filter 310 is iterated the filter gains approach their steady state values.

Measurement Noise Covariance Matrix

The measurement noise, z(k), is defined as:

$$z(k) = \begin{bmatrix} z_1(k) \\ z_2(k) \end{bmatrix} = \begin{bmatrix} \text{Range Measurement Noise} \\ \text{Velocity Measurement Noise} \end{bmatrix}$$

The range and velocity measurements are derived
 5 directly from the TOA raw parameter 230 (FIG. 3) and FOA
 raw parameter 225 (FIG. 3) respectively. Since the
 variances of TOA raw parameter 230 and FOA raw parameter
 225 are known, the range and velocity variances can be
 determined. The measurement processes are mean zero
 10 (i.e., no bias error), and hence the variance = $E\{z_i^2(k)\}$ which is what is needed to define terms in the
 R matrix.

In the preferred embodiment, FOA raw parameter 225
 standard deviation is:

$$15 \quad s_f = 31.97 \text{ Hz at } 4.1 \text{ dB Eb/No}$$

Hence,

$$s_v = s_f \frac{c}{f_c} = 31.97 \frac{3 \times 10^8}{1625 \times 10^6} = 5.9$$

m/s

20 and,

$$s_v^2 = 34.84 \text{ m}^2/\text{s}^2$$

Likewise, TOA raw parameter 230 standard deviation
 is:

$$25 \quad s_t = 0.0028 \text{ ms at } 4.1 \text{ dB Eb/No}$$

Hence,

$$s_r = c s_t = 3 \times 10^8 \times 0.0028 \times 10^{-3} = 840.0 \text{ m}$$

and,

$$30 \quad s_r^2 = 705,600 \text{ m}^2$$

As for the off diagonal terms, these terms are the
 cross-correlations between the range and velocity
 measurements. These measurement errors are considered
 35 uncorrelated for the following reasons:

(i) Under static conditions, TOA raw parameter 230 is a more robust measurement than FOA raw parameter 225. It has a very small standard deviation over its operating signal-to-noise ratio where FOA raw parameter 225 has a much broader range;

(ii) Under real orbital conditions, TOA raw parameter 230 and FOA raw parameter 225 processes are not stressed at the same time. TOA raw parameter 230 has large error values at low elevation angles where radial velocity is maximum and acceleration is minimum, and FOA raw parameter 225 has large error values at high elevation angles where radial acceleration is maximum and velocity is minimum; and

(iii) Under link blockage or fading conditions, no FOA raw parameter 225 and TOA raw parameter 230 updates are made to vector filter 310 (or the tracking loop for that matter) so correlated error under this condition is not a consideration.

The R matrix for this filter implementation is:

$$R(k) = E\{z(k) z^T(k)\}$$
$$= \begin{bmatrix} E\{z_1^2(k)\} & E\{z_1(k)z_2(k)\} \\ E\{z_2(k)z_1(k)\} & E\{z_2^2(k)\} \end{bmatrix}$$

Process Noise Covariance Matrix

Filter development relies on the modeling of radial acceleration. The true behavior of the acceleration is that it is near zero when satellite 100 is viewed at low elevation angle and is some maximum negative value at zenith, satellite 100 has slowed down relative to mobile subscriber unit 200. The magnitude of the acceleration then reduces back to zero as the elevation angle decreases back to zero. Non-overhead passes have a similar profile without the maximum acceleration magnitude being reached. The acceleration from one transmission from mobile subscriber unit 200 to the next

will have significant correlation as the acceleration is a slow varying process. However, vehicular motion of mobile subscriber unit 200 may introduce other extraneous accelerations which may reduce the correlation from transmission to transmission.

In the preferred embodiment, the acceleration rate-of-change is characterized with values of $\pm 0.5 \text{ m/s}^3$ for the overhead pass and $\pm 0.3 \text{ m/s}^3$ for the side pass utilized. Maximum acceleration occurs when satellite 100 is directly overhead of subscriber unit 200. In the preferred embodiment, the acceleration rate of change is maximum about a minute before and after satellite 100 is directly overhead subscriber unit 200 and has a magnitude of about 0.5 m/s^3 . This corresponds to about a 70° elevation angle.

A histogram, $p_{a'}(a')$, of the acceleration rate-of-change may be constructed to evaluate the variance of the process.

$$E\{a'(k) a'(k)\} = \int_{-\infty}^{\infty} a'^2 p_{a'}(a') da' = 0.053$$

m^2/s^3

Knowing the acceleration rate-of-change variance in the preferred embodiment, the covariance matrix can now be evaluated.

$$\begin{aligned} Q(k) &= E\{w(k) w^T(k)\} \\ &= E\left\{ \begin{bmatrix} T^3/6 \\ T^2/2 \\ T \end{bmatrix} a'(k) \begin{bmatrix} T^3/6 & T^2/2 & T \end{bmatrix} a'(k) \right\} \\ &= \begin{bmatrix} T^6/36 & T^5/12 & T^4/6 \\ T^5/12 & T^4/4 & T^3/2 \\ T^4/6 & T^3/2 & T^2 \end{bmatrix} E\{a'(k) a'(k)\} \end{aligned}$$

setting $T=0.36 \text{ sec}$ (the feedback parameter loop update rate of the preferred embodiment) and using the result for the expected value of a'^2 , the Q matrix has a value of:

$$Q(k) = \begin{bmatrix} 3.51e-6 & 2.67e-5 & 1.48e-4 \\ 2.70e-5 & 2.23e-4 & 1.24e-3 \\ 1.48e-4 & 1.24e-3 & 6.87e-3 \end{bmatrix}$$

Filter Initialization

5 Initial values are needed for the filter state variables ($r(0)$, $v(0)$ and $a(0)$) and the 3x3 prediction mean square error matrix $P(0)$.

The state variables $r(0)$ and $v(0)$ are initialized by the range and velocity estimates determined during when
 10 subscriber unit 200 is performing a synchronization mode while it is "pulling in" to meet the criterion of communication parameters for communication link 105. $a(0)$ is initialized by differencing two velocity measurements; $[v(1) - v(0)] / T$. Note that to
 15 initialize $a(k)$, two measurements are needed. Since communication link 105 is now operating in Traffic mode and hence, in the preferred embodiment, these measurements are about 0.36 sec apart. In subscriber unit 200, tracking loops will run without vector filter
 20 310 until these measurements are available to the filter.

The mean square error matrix $P(k)$ should be initialized by the variance of the initial state measurements. The $P(0)$ matrix is given by:.

25

$$P(0) = \begin{bmatrix} E\{r \cdot r\} & E\{r \cdot v\} & E\{r \cdot a\} \\ E\{v \cdot r\} & E\{v \cdot v\} & E\{v \cdot a\} \\ E\{a \cdot r\} & E\{a \cdot v\} & E\{a \cdot a\} \end{bmatrix}$$

where,

$$E\{r \cdot r\} = s_r^2$$

$$E\{r \cdot v\} = E\{v \cdot r\} = 0$$

30 $E\{r \cdot a\} = E\{a \cdot r\} = 0$

$$E\{v \cdot v\} = s_v^2$$

$$E\{v \cdot a\} = E\{a \cdot v\} = E\left\{ \frac{v_1 - v_0}{T} \right\} \quad v_1 = \frac{s_v^2}{T}$$

and,

$$E\{a \cdot a\} = E\left\{ \frac{v_1 - v_0}{T} \quad \frac{v_1 - v_0}{T} \right\} = \frac{2s_v^2}{T^2}$$

Updating the matrix:

$$P(0) = \begin{bmatrix} s_r^2 & 0 & 0 \\ 0 & s_v^2 & \frac{s_v^2}{T} \\ 0 & \frac{s_v^2}{T} & \frac{2s_v^2}{T^2} \end{bmatrix}$$

5 Substituting the values given in the last section for s_r^2 and s_v^2 and using $T=0.36$ sec since the initial values are calculated over a four frame interval, the initial value, in the preferred embodiment, for the error covariance matrix is:

10

$$P(0) = \begin{bmatrix} 705600 & 0 & 0 \\ 0 & 34.84 & 96.78 \\ 0 & 96.78 & 537.65 \end{bmatrix}$$

FIG. 5 depicts a block diagram of an acceleration compensator in accordance with a preferred embodiment of the present invention. When a link interruption occurs, the loop tracking filter combines the geometric matrix A, the previous state estimate matrix, and acceleration compensation data from aircraft avionics. In order to correctly predict the link parameters, the loop tracking filter must account for the radial acceleration of the link which comprises the satellite and the aircraft accelerations. The tracking loop filter calculates the radial range, velocity, and acceleration based on the observations made of Doppler offset and propagation delay. These radial parameters have components due to the aircraft dynamics as well as the space vehicle components. The radial acceleration can be expressed as:

30 $\vec{a} = \vec{a}_{sv} + \vec{a}_A$
 where,

a is the scalar value of the composite radial acceleration;

→

a_{SV} is the satellite acceleration vector;

→

a_A is the aircraft acceleration vector; and

• denotes the vector dot product.

When the link outage occurs and no observations of the satellite are available, the last estimate of the satellite component of radial acceleration should be held constant and the aircraft portion should be continually updated. However, in order to do this, the two components of the radial acceleration must be isolated.

In airborne applications which use a gimbaled dish antenna for geosynchronous satellite communications, a bore sight accelerometer can be mounted to the antenna. The boresight accelerometer gives a continuous reading of the aircraft acceleration in the direction of the satellite with a significant satellite component. However, in many airborne applications, gimbaled antennas are replaced by a patch or fin type antennas and bore sight accelerometers are not desirable since spatial tracking is lost during a link blockage and the output of the accelerometer is inaccurate during an outage.

In the preferred embodiment, an aircraft accelerometer vector is derived from the aircraft inertial navigation system combined with the link observations. The composite scalar acceleration is calculated by the Kalman filter based on observations of the link Doppler and propagation delay. The aircraft acceleration vector may be calculated from the velocity, roll, pitch, yaw, and heading information available from the aircraft inertial navigation system. The satellite

acceleration vector is then calculated by dividing the scalar observation by the aircraft acceleration vector.

$$\vec{a}_{SV} = \vec{a} / a_A$$

5

All three components are now known and when a link outage occurs, the satellite term is held constant at the last estimate and the aircraft term is continuously updated. The computation needed to perform this calculation is shown in FIG. 5.

FIG. 6 is a flowchart for predicting dynamic communication parameters in a dynamic communication system, in accordance with a preferred embodiment of the present invention. In the preferred embodiment, mobile subscriber unit 200 performs link outage protection procedure as shown.

In a task 504, mobile subscriber unit receives acceleration data from an aircraft inertial navigation system. The mobile subscriber unit, in the preferred embodiment, is located on an aircraft with the aircraft capable of generating navigational data from which acceleration may be calculated. In a task 505, mobile subscriber unit 200 initiates the establishment of communications with satellite 100 by initiating communications as directed by a user of mobile subscriber unit 200 either in response to notification that an incoming call is pending or as initiated by the user.

A task 510 then receives feedback communication parameters from satellite 100 either from an independent broadcast channel or in a maintenance portion of communication link 105. These feedback communication parameters, in the preferred embodiment, comprise frequency and timing variances associated with transmission of data from mobile subscriber unit 200 to satellite 100 as evaluated by satellite 100.

5 A query task 515 then evaluates if synchronization is completed. Synchronization is complete when communication parameters are sufficiently accurate that satellite 100 permits mobile subscriber unit 200 to communicate on a tighter-tolerance traffic channel. Also, synchronization is complete, in the preferred embodiment, when the matrices of vector filter 310 are initialized.

10 A task 550 proceeds when the learning or synchronization of query task 515 is not complete. In task 550, the feedback or raw parameters of communication link 105 are employed for communicating with satellite 100. These feedback parameters provide larger "pull-in" increments while coarse adjustment of
15 communication parameters is underway.

When synchronization is completed, a task 520 utilizes the communication parameters emerging from vector filter 310. These parameters more incrementally continuous and provide a smoothing effect to
20 communication parameters employed on communication link 105. This smoothing provides a collateral benefit to communication link 105 in that vector filter 310 tracks variations in communication parameters and anticipates future changes to these parameters. This anticipation
25 and employment of these anticipated communication parameters reduces the frequency of transmission of feedback parameters on communication link 105.

A task 521 calculates the acceleration vector for the satellite. When a link outage occurs and no
30 observation of the satellite are available, the last estimate of the satellite component of radial acceleration is saved and held constant while the aircraft portion is continually updated during the outage.

35 A query task 530 evaluates communication link 105 to determine if the link remains intact or if an outage has occurred due to link blockage. If link interruption has

not occurred, then processing returns to task 510 to listen for any subsequent transmissions of feedback parameters to be incorporated into future predictions of communication parameters.

5 When an link outage is detected, a task 531 retrieves current acceleration data for computation with predicted values as discussed in FIG. 5. A task 535 predicts future communication parameters for use in communication link 105. These parameters are generated
10 when link detect status 235 disables the input path and vector filter 310 cycles producing predictions of communication parameters.

 A task 540 then employs these predicted communication parameters by attempting to transmit to
15 satellite 100 using these predicted communication parameters. These predicted parameters roughly track the actual communication parameters necessary to reestablish communications.

 A query task 545 then reevaluates communication link
20 105 to determine if the link blockage has ceased. If the link has not been successfully reestablished, then processing returns to task 535 for a subsequent prediction of the communication parameters presently necessary to attempt a successive re-establishment of
25 communication link 105. This iterative prediction of subsequent parameters may continue indefinitely until the link is recovered or may be terminated after a predetermined number of attempts. Because the prediction of subsequent communication parameters has
30 inherent error which Depends on the number of stages utilized in vector filter 310, the prediction of communication parameters will drift from actual necessary values for the re-establishment of communication link 105. A predetermined timeout or an
35 automatic re-initiation of communications as described in task 505 may be employed.

○
If re-establishment of communication link 105 is detected in query task 545, then processing passes back to task 510 for reception of feedback communication parameters and reinitialization of vector filter 310.

5 The present invention has utility in maintaining synchronization with a satellite and a mobile subscriber unit during link blockages such as those due to control surface blockage of the link while the aircraft performs maneuver.

10 The present invention has been described above with reference to a preferred embodiment. However, those skilled in the art will recognize that changes and modifications may be made in this preferred embodiment without departing from the scope of the present
15 invention.

CLAIMS

What is claimed is:

1. In a wireless communication system, a method of
5 restoring a communication link between a mobile base
station and a mobile subscriber unit following an
interruption of said communication link comprising the
steps of:

10 establishing said communication link having dynamic
communication parameters;

revising said dynamic communication parameters as
orientation changes between said mobile base station and
said mobile subscriber unit;

15 upon an interruption of said communication link,
providing acceleration data characteristic of said
mobile subscriber unit;

said mobile subscriber unit predicting current
dynamic communication parameters in part from said
acceleration data; and

20 upon termination of said interruption of said
communication link, said mobile subscriber unit
employing said current dynamic communication parameters
for restoring said communication link.

25 2. The method as recited in claim 1 further
comprising the step of generating said acceleration data
representative of motion of said mobile subscriber unit.

3. The method as recited in claim 1 wherein said revising step comprises the steps of:

transmitting on said communication link using said
5 dynamic communication parameters;

evaluating at said mobile base station an accuracy of said dynamic communication parameters employed by said mobile subscriber unit;

when said accuracy of said dynamic communication
10 parameters exceeds a threshold, transmitting feedback communication parameters denoting adjustments to said dynamic communication parameters to said mobile subscriber unit;

receiving said feedback communication parameters;
15 and

employing said feedback communication parameters to generate said dynamic communication parameters for use in subsequent transmissions by said mobile subscriber unit.

20

4. The method as recited in claim 3 wherein said employing step further comprises the steps of:

when said mobile subscriber unit receives feedback communication parameters, incorporating said feedback
25 communication parameters into said dynamic communication parameters; and

else generating dynamic communication parameters from previous ones of said dynamic communication parameters.

30

5. The method as recited in claim 4 further comprising the step of employing a Kalman-type filter in said incorporating and generating steps.

35

6. The method as recited in claim 1 wherein said predicting step further comprises the steps of:

filtering previous ones of said dynamic
communication parameters;
incorporating said acceleration data; and
predicting current dynamic communication parameters.

5

7. The method as recited in claim 6 further
comprising the step of attempting to reestablish said
communication link using said current dynamic
communication parameters as said dynamic communication
parameters.

10

8. The method as recited in claim 6 further
comprising the step of employing a Kalman-type filter
for performing said filtering steps.

15

9. The method as recited in claim 1 further
comprising the steps of employing Doppler frequency
offset and propagation delay as said dynamic
communication parameters.

20

10. The method as recited in claim 1 wherein said
mobile base station is an orbiting satellite and said
mobile subscriber unit is aboard an aircraft.



Application No: GB 9719442.7
Claims searched: all

Examiner: Nigel Hall
Date of search: 11 November 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK CI (Ed.O): H4L (LDC, LDLX, LDSX, LDRR)

Int CI (Ed.6): H04B 7/00, 7/005, 7/01, 7/015

Other: Online: WPI, INSPEC

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	GB 2307376 A (MOTOROLA)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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